Solar Heavy Ion Heinrich Fluence Spectrum at Low Earth Orbit

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Abstract

Solar heavy ions from the JPL Solar Heavy Ion Model have been transported into low earth orbit using the Schulz cutoff criterion for L-shell access by ions of a specific charge to mass ratio. The NASA Brouwer orbit generator was used to get L values along the orbit at 60 second time intervals. Heavy ion fluences of ions $2 \leq Z \leq 92$ have been determined for the LET range 1 to 130 MeV-cm^2/mg by 60, 120 or 250 mils of aluminum over a period of 24 hours in a 425 km circular orbit inclined 51°. The ion fluence is time dependent in the sense that the position of the spacecraft in the orbit at the flare onset time fixes the relationship between particle flux and spacecraft passage through high L-values where particles have access to the spacecraft.

Introduction

It is increasingly important to assess the radiation hazard for devices in low earth orbits because of the decreasing availability of new radiation hard electronic devices. Single event effects (SEE) due to galactic cosmic rays and energetic solar event particles are ameliorated somewhat by the earth's magnetic field. However, very high energy ions can penetrate to low earth orbits depending on the L-value of the spacecraft, the ion energy and charge to mass ratio. A cutoff energy below which an ion with specific charge to mass ratio can not penetrate to the spacecraft location can be estimated by the Schulz approximation.

A program has been constructed to calculate the Heinrich fluence of ions $2 \leq Z \leq 92$ over several orbits. A NASA Brouwer orbit generator was used to calculate spacecraft position in B-L space as well as geographical coordinates every 60 seconds. A solar heavy ion model developed at JPL using observed average solar ion abundance ratios and normalized by IMP-8 alpha particle statistics was invoked at each 60 second orbit point to calculate the Heinrich fluence. The Heinrich fluence is modified only integrating over ion energies above the ion cutoff energy. Shielding has been taken into account so that the Heinrich fluence was determined at the device inside of a aluminum shield. The orbit integration was carried out for a 24 hour period.

JPL Heavy Ion Model

Ion composition of individual solar particle events observed in interplanetary space can be highly variable. Ion composition averages taken over a series of solar flares during a solar cycle can be related to observed solar photospheric abundance ratios after correction for propagation effects

JPL Heavy Ion Model

Ion composition of individual solar particle events observed in interplanetary space can be highly variable. Ion composition averages taken over a series of solar flares during a solar cycle can be related to observed solar photospheric abundance ratios after correction for propagation effects which depend on the ionic charge to mass ratio and the first ionization potential (FIP) [6,7,8]. The model presented here uses the solar photospheric abundances [7,9] to derive solar energetic particle fluxes in interplanetary space. The ion model includes ion atomic numbers $2 \leq Z \leq 92$, helium through uranium. [16].

Solar heavy ion flux is modeled by the following parametric equation [14]:

$$(1) \quad j(E,t,Z) = J_0 \frac{E}{E_0} e^{-\sqrt{\frac{E}{E_0}}} e^{-\frac{(t-T_0)}{\tau}} \frac{A_s(Z)}{A_s(Si)} \left[\frac{Q/M(Z)}{Q/M(Si)}\right]^{\alpha} \frac{S[\phi_0 - \phi(Z)] + S_0}{1 + S_0}$$

$$\text{units of } (cm^2 \cdot s \cdot sr \cdot MeV/nuc)^{-1}$$

where $S(x) = 0$ if $x<0$

$S(x) = 1$ if $x>0$

Z = atomic number

$Q/M(Z)$ = ionic charge/mass (Table 2)

E = ion energy/nucleon, (MeV)

t = time

$\phi(Z)$ = first ionization potential (FIP), eV (Table. 2)

$A_s(Z)$ = solar photospheric abundance ratio ('1'able 2)

E_0 = ion spectral index, 0.3 MeV

T_0 = solar flare onset time, O

τ = solar flare decay constant, 8.333 days

α = power law index for Q/Al, 67

$S_0(Z)$ = FIP step factor, ,3??")5, S_0( ) He) 138

ϕ_0 = location of FIP step, 1 0. eV

J_0 = normalization factor (Table 1)

integration over time, energy and solid angle yields the fluence of each ion species in the flare. The normalization constant JO determines the magnitude of the. event. It must be emphasized that this model is based on the averages presented in Breneman and Stone ["/],

Parametric Choices

The key parameters $\alpha = .67$, $S_0 = .275$, $\phi_0 = 10eV$ and $A_s(6 \le Z \le 30)$ were taken from the study of 10 solar flares [7] between 1977 and 1982. The solar abundance ratios $A_s(2 \le Z \le 5)$ and $A_s(Z>30)$ were taken from Anders and Grevesse [9]. The FIP step factor for helium $S_0 = .138$ was taken from Retunes et al. [6]. The values of FIP, $\phi(z)$ were taken from the Handbook of Chemistry and Physics [11]. The values of $Q/M(3 \le Z \le 30)$ were obtained from 11,11, Breneman's thesis **[8].** The value of $Q/M(Z>30)$ were derived by extrapolating the ionic charge curves presented in Figure 4.1 from Breneman [8]. Extrapolation can be the source of large errors, but an estimate of the maximum error due to use of different slopes for extrapolation of the Q vs Z curves is -60°/0. The value $E_0 = 0.3MeV$ was determined from the October 1989 solar flare. The value $\tau = .833day$ (20 hours) is a generally recognized solar flare decay constant. The solar flare onset time was set $T_0 = 0$. The normalization constant Jo varies with the magnitude of the flare. The integrated ion fluence is linear function of Jo The heavy ion fluence can be scaled to the helium fluence by adjusting the value of JO. Table 1 gives values of JO vs cumulative probability of occurrence for a solar flare with ion fluences equal to those gotten by integrating the. spectrum (1).

Cutoff Energy in a Dipolar Magnetic Field

The adiabatic theory of charged particle motion in a dipolar magnetic field is based on the hypothesized smallness [15] of the quantity

$$\epsilon = 5.146(A/Z)\times 10^{-5}[E(E+1863)]^{1/2}L^2 \qquad (2)$$

where E is the particle energy in MeV/nucleon, A is the mass number, and Z is the charge-state number. It is assumed that the critical value for magnetic trapping is 1/3 and for comic-ray cutoff is 3/4. The cutoff energy E can be expressed as

$$E = \frac{-1863 + \sqrt{(1863)^2 + 4\left[1.455\times 10^{4}\frac{Q/M}{L^2}\right]^2}}{2} \qquad (3)$$

where c has been assumed to be 3/4.

Calculation of the LET Spectrum

The LET spectrum (Heinrich flux) was calculated by integrating the flux of all particle species which have stopping powers (or LET), $(1/\rho)dE/dx$ MeV-cm^2/mg, above a specific value. The Heinrich flux pertinent to the production of SEUs is derived from the heavy ion flux after transport through the shielding. LET as a function of incident particle energy has a relative maximum for each ion species. Therefore, all values of LET > a specified value lie between a lower and an upper energy limit E_1 and E_2. For specific path length through the sensitive volume, integrating, the energy spectrum of that ion species between E_1 and E_2 gives the contribution of that ion species to the LET spectrum

$$(3)\quad HF(Z,LET,x,L) = \int_{E_1(Z,LET,L)}^{E_2(Z,LET,L)} dE\; j(E)_{Z,inside,x}$$

These calculations are performed on the transported fluxes "inside the shield". The calculations can be performed on the fluxes "outside the shield" by adjusting the limits of integration.

$$(4)\quad HF(Z,LET,x,L) = \int_{E_1'(Z,LET,x,L)}^{E_2'(Z,LET,x,L)} dE\; j(E)_{Z,outside}$$

where x = shield thickness
LET = value at which LET spectrum is being determined
Z = ion species
$j(E)_{Z,inside,x}$ = energy spectrum of Z^{th} species inside shield
$j(E)_{Z,outside}$ = energy spectrum of Z^{th} species outside shield
L = Pathlength in the sensitive volume (2 microns)

The effect of shielding is to reduce particle energies after transport, shifting the spectrum to lower energies. Therefore., to accomplish the same integration but over the unshielded spectrum take the energy limits corresponding to a specific LET inside the shield and find the corresponding energies (E_1',E_2') outside the shield using range tables for that species

An effective Heinrich fluence calculation in which the path length distribution in the sensitive volume is taken into account was not performed due to the excessive computer time required. All ions are assumed to enter normal to the device surface. The thickness of the sensitive. volume was assumed to be 2 microns.

The orbital integration was accomplished by taking the L-values gotten from the NASA Brouwer Orbit Generator and calculating a cutoff energy using the Schulz approximation. If the lower limit E_1' in (4) was less than the cutoff energy at that orbit location, the lower limit was replaced with the cutoff energy. The integration is described by

$$(5) \quad HF(LET,x) = 4\pi \sum_{Z=2}^{92} \sum_{t=0}^{24} HF(z,LET,x)\Delta t$$

where Δ=60 seconds.

The Heinrich fluence results for two orbits (1) 425 km circular, 51° inclination and (1) geosynchronous orbit are shown in Figure 1.

Conclusion

A physical model based on experimental observations and theory has been developed which accounts for heavy ions $2 \leq Z \leq 92$ using a formalism which incorporates solar abundances, Q/M (ionic charge/mass) and first ionization potential (FIP) dependence reflecting processes at work in the solar corona. An exponential time dependence has been assumed which gives more conservative peak fluxes at t=0 than would be the case for a time dependence similar to solar protons. Additional conservatism is introduced into the model by the assumption that a solar particle event is a single exponential event in time. In reality, large solar particle events are often multiple events occurring close together over a period of several days. The effect of these assumptions is to over estimate the peak Heinrich flux but since the model has been normalized to the total event alpha fluence, it gives reasonable heavy ion event fluences.

The introduction of the ion cutoff energy due to the shielding effect of the earth's magnetic field of getting an engineering estimate of the solar particle event Heinrich Fluence at low earth orbit. Figure 1 shows the calculated Heinrich fluence for the first day of a flare for two orbits: (1) 425 km circular, 51° inclination, a typical space station orbit and (2) geosynchronous orbit 6.6R_e. The lower orbit show about an order of magnitude less fluence than at geosynchronous orbit. All solar flares vary in ionic composition and spectral shape. A softer energy spectrum would, of course, enhance the shielding effect of the magnetic field at low earth orbit. A reasonable engineering model has been constructed for the estimation of the effects of heavy ions at low earth orbit.

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Table 1. Average Flux Normalization Constants

%, Cum. Prob.	J_0
99	3.0
90	.3
80	.1
70	.05
50	.02
30	.005

Z Q/M FIP ABUNDANCE Z Q/M FIP ABUNDANCE

12.60413.598 0.2790E+05 470.468 7.576 0.4860E-06
2 1.30224.S870.2720E+04 480.446 8.993 0 1 (',101 -05
31.133 5.392 O. S71OE-O4 490.448 5.786 ().1840106
41.242 9.3220.7300E-06 500.439 7.344 0.3820E 05
51.214 8.2980.2120E-04 510.433 8,(,41 0.3090E 06
61.24511 .2600 .6490E+OI 520.419 9.009 O 4810E-05
71,172 14.S340.2775EW1 530,4?6 10.451 0.9000E-06
81.148 13.6180.2290EW2, 540.41712. 130(1,4-/0(11:-05
91.12517.422 0.11OOE-O2 550.417 3.894 (). 3720I 06
101.208 21.5640.3140E-101 560.407 5.212 0.4490E-05
111.146 5.139 0.6700)3-01 570.409 5.577 0.4460E-06
121.167 7.6460.1089E-tOl 580.411 5.470 O 1136} .05
131.068 5.9860.8370E-01 590.413 5.420 (), 1669I (I6
141,000 8.151 0.1000E+01 600.408 5.490 O 8279I-06
150.914 10.4860.9240E-02 610.000 0.000 0.0000E+00
160.875 10.3600.4600E+O0 620.400 5,6300 2582} .-06
170.797 12.9670.9600E-02 630.400 5.670 O '9'/ 301 -07
180.794 15.7590.I020E+O0 640.391 6.140 (i3300E-06
190.7604.341 0.3900E-02 650.389 5.850 0.6030E 07
200.763 6.113 0.8200E-01 660.387 5.930 0.3942E 06
210.703 6.540 O.31OOE-O3 670.385 6.020 0.8890E-07
220.688 6.8200.4900E-02 680.384 6.100 0.2508E-06
230.674 6 7400.4800E-03 690.384 6.180 0.3780E-07
240.690 6.7660.1830E-01 700.377 6.254 0.2479E-06
2S 0.667 7.435 0.6800E-02 710.379 5.426 0.3670E 07
260.654 7.8700. 1270E+0172 0.37S 7.()() O. 1540I06
270.622 7.860 0.1870E-01 730.374 7.890 0,70'/'01; 07
280.617 7.635 0.46501; 01 74 0.37] 7,9800 1330E06
290.S60 7.72.6 0.5700E-03 750.370 7.880 05] '/()]: 1)7
300.S29 9.394 0.1610E-02 760.366 8.700 0 6750E-06
3] 0.570 5.999 0.3780E-04 770.366 9. 100" (), 661 of . 06
320.541 7.8990.1 190E-03 780.364 9.000 0.1340I,- 05
33 0.542 9.810 0.6560E-05 790.364 9.225 0.18701 06
34 0.517 9.752 0.62] 0E-04 800.360 10.437 0.3400E 06
35 0.S32 11.814 0.1180E-04 81 0.3S7 6.108 0.1840E-06
360.S08 13.999 0.4500E-04 82 0.3S5 '7.4)6 (1.31 50E-05
370.510 4.177 0.7090E-05 830.356 7.289 (). 1440E-06
38 0.50] 5.695 0.23 50E-04 840.000 0.000 0.0 000E-00
390.503 6.3800.4640E-05 850.000 0.()()() 0.0000E-00
400.505 6.8400. 1140E-04 860.000 0.000 0.0000E-00
410.495 6.8800.6980E-06 870.000 ().()()() 0. 0 000E+00
420.477 7.099 0.2 550E-05 880.000 0.000 0.0000E+00
430.000 0.0000 .0000E-i 00 890.000 0.000"0 0000I :100
440.472 7.3700.1860E-05 900.341 S,S00 0 3350E-07
450.474 7.4600.3440E-06 910.000 0,()()() 0 0000E+00
460.466 8.340 0.1390E-05 920.338 5,S00 0 9000E-08

Zeros indicate an element absence in the observed solar spectrum